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Compaction and organic matter retention in mixed-conifer forests of California: 20-year effects on soil physical and chemical health

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ABSTRACT

Soil resilience following harvest disturbance was studied at nine Long-Term Soil Productivity sites across the Sierra Nevada mountain range of California. We tested whether soil compaction, surface organic matter (OM) retention, and plant diversity have lasting effects on soil C, N, bulk density, or porosity. Study treatments following clearcut harvesting included soil compaction (none, moderate, severe) in factorial combination with three levels of OM retention (harvest slash retained, [OM2]; no slash retained, [OM1]; bare soil, [OM0]) and two plant diversity treatments (trees only; trees and shrubs). The sites encompassed a wide range in soil OM (5 to 12%) and clay content (5 to 36%) and represented common soil types in Sierran forests. At year 10, soil bulk densities were 10–29% greater for severely compacted compared to non-compacted plots across sites, corresponding to an average loss of 9–11% total porosity. Partial recovery was found by year 20, as bulk densities were 2–17% higher for compacted compared to non-compacted plots. In contrast to these physical responses, compaction had no adverse effect on soil C and N content at either year 10 or 20. Slash retention (OM2 versus OM1) and plant diversity treatments also had few effects on soil properties with the exception of a small increase in bulk density in the absence of shrubs, presumably due to reduced root and surface litter input. A more pronounced response was found following complete removal of surface organics (OM0), which produced a study-wide decline (12–17%) in soil C, N, and bulk density by year 20. All treatment responses were fairly consistent across sites, regardless of site differences in clay or soil OM content. Our results suggest substantial tolerance of soil C and N to harvest disturbance in Sierra Nevada forests despite a sustained change in soil physical properties and highlight the importance of the O horizon to long-term soil health.

1. Introduction

Maintaining soil health and productivity is a long-standing commitment in the conservation and management of California forests, where wildfire, drought, timber harvesting, insect outbreaks, forest fragmentation, and urban expansion are unremitting (California Department of Forestry and Fire Protection, 2018). How soil responds to these external disturbances is difficult to predict, however, owing to the diversity of soils, forests types, climatic conditions, and forest management practices and objectives. Thus, developing practicable knowledge of soil resilience across temporal and spatial scales is a basic requisite to complement our current understanding of soils' influence on forest vegetation growth and diversity; water capture, storage, and release; and climate change mitigation and adaptation (Binkley and Fisher, 2019). The Long-term Soil Productivity study (LTSP) was established in 1989 across the US and Canada to address this need, specifically to refine our knowledge of timber harvesting effects on soil physical, chemical, and biological resilience. Soil compaction and organic residue management were identified as the core variables most suitable for study given their well-recognized effects on site productivity (Powers, 2006). Accordingly, the fundamental LTSP hypotheses were: (1) critical changes in soil porosity and organic matter content have lasting effects on site productivity by altering soil air, water, nutrient balance, and energy flow; (2) negative impacts from harvesting are reversible with time; and (3) impacts to soil properties are not universal, instead they vary by climate and soil type.

Soil compaction and its effect on forest growth and function is a long-standing forestry concern (Munns, 1947; Steinbrenner and Gessel,

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1955). At-risk processes are numerous (e.g., soil aeration and gas exchange, water infiltration, erosion, nutrient and water availability, root growth, site productivity, hydrologic function) and underscore scientific efforts to better understand, assess, and, ultimately, help prevent or restore compacted soils (Page-Dumroese et al. 2010; Cambi et al. 2015). Effects of compaction from harvesting equipment can be difficult to predict given site-specific differences in soil properties (e.g. soil OM, clay, rock, and water content) and the intensity of local logging practices (Han et al., 2009). Given this uncertainty, several best management practices are often recommended to limit the severity and extent of soil compaction in most situations, such as harvesting when soils are dry or frozen; use of dedicated skid trails to restrict areas of cumulative soil disturbance; use of low-ground-pressure harvest equipment with tracks or wide tires; limiting the number of passes by machinery in areas where skid trails are impractical; and harvesting on top of heavy slash in cut-to-length operations (Cambi et al., 2015).

It has not been universally demonstrated that soil compaction is detrimental to vegetation growth (Froehlich et al., 1986; Ampoorter et al., 2007; Moghaddas and Stephens, 2008). In fact, findings from LTSP sites across the US and Canada have identified a net positive response of tree growth for the first decade or so in compacted soil (Ponder et al., 2012). Although this seems counterintuitive, Ponder et al. (2012) noted that most LTSP sites are located on well-drained, sandy soils, lending credence to early findings that soil water-holding capacity, and consequently vegetation growth, increases when sandy soils are compacted (Gomez et al., 2002). Recent results from California LTSP sites do not support this assertion, however, as 20-year stand growth was generally unaffected by compaction in both coarse and fine-textured soils (Zhang et al., 2017). Others have found that growth responses vary substantially by tree species due to unique rooting strategies, with aspen (*Populus grandidentata*) and white spruce (*Picea glauca*) particularly sensitive to soil compaction in northern latitudes (Ponder et al., 2012; Kranabetter et al., 2017).

Organic matter removal and its effect on soil productivity is another continuing forestry concern (Boyle et al., 1973). Important questions facing managers are: should harvest slash be left on-site following traditional cut-to-length operations to optimize nutrient capital, soil C, erosion reduction, and microclimate conditions? Are the benefits of full-tree extraction for use in bioenergy production or for reducing wildfire hazard acceptable trade-offs despite potential reductions to site C, N, and soil quality? No clear answers to these questions have been offered in comprehensive *meta*-analyses and literature reviews (Thiffault et al., 2011; Clarke et al., 2015; Wan et al., 2018). In fact, most syntheses point to inconclusive, site-specific responses that vary with climate, soil texture, tree species, organic matter content, harvest practice, and soil nutrient content. The primary impact of whole-tree harvesting on site productivity results from disturbance of the O horizon, not the mineral soil, and most changes appear to be moderate (<15% change) and short-lived (<20 years). For example, Morris et al. (2019) found little difference in soil chemical properties or 20-year tree growth between whole tree and bole-only harvesting across multiple Canadian LTSP sites. Detrimental change only arose when the forest floor and upper 5 cm of mineral soil were completely removed from these nutrient-poor sites. This finding adds to observations that nutrient-poor sites with shallow soils may experience productivity declines without full retention of surface organics (Achat et al., 2015).

Here we report on compaction and OM retention effects on a wide range of forest soils in the California Sierra Nevada. Our objectives were to (1) determine the effects of compaction and OM retention on soil C, N, bulk density, and total porosity, (2) identify the extent of site recovery 10 and 20 years after treatment implementation, and (3) evaluate disturbance responses across a diversity of soil types common in Sierran forests. We hypothesized that the extreme LTSP treatments would result in long-lasting change in soil C, N, and bulk density – presumably through reduced input of surface litter C and modified soil gas and water movement – and that these effects would be greater in fine-textured soil compared to sandy soils.

2. Methods

2.1. Study sites

Nine sites were selected within the Sierra Nevada mixed-conifer forest type, the major timber producing forests of California (Fig. 1). Overstory species included ponderosa pine (*Pinus ponderosa*), white fir (*Abies concolor*), Douglas fir (*Pseudotsuga menziesii*), sugar pine (*P. lambertiana*), and incense cedar (*Calocedrus decurrens*). Dominant soil series (on an acreage basis) within the forest type were then identified by National Forest personnel using soil survey maps from the Natural Resource Conservation Service and served as the primary land base for site selection. Final site selection met the following criteria, (1) presence of a mature forest, 100–200 years in age; (2) upland forest with low- to moderate slope (<15%); (3) uniform stocking level and stand structure; (4) 15 ha minimum stand size (e.g., Fig. 2b); and (5) minimal prior disturbance of soil physical properties based on visual inspection. Site and soil characteristics are presented in Table 1.

All sites are classified as 'warm temperate dry' (Lugo et al. 1999) with a Mediterranean climate of warm, dry summers and cool, wet winters. Most precipitation occurs between November and April, predominantly as rain at low elevation sites (e.g., Challenge) and snow and rain at higher elevation sites (e.g., Owl). Common understory vegetation across sites is dominated by woody shrubs including deerbrush (*Ceanothus integerrimus*), snowbrush (*C. velutinus*), mountain whitethorn (*C. cordulatus*), and greenleaf manzanita (*Arctostaphylos patula*), with hardwood trees also present at lower elevation sites (tanoak [*Notholithocarpus densiflorus*], madrone [*Arbutus menziesii*], mountain dogwood [*Cornus nattallii*], California black oak [*Quercus kelloggii*]). Scattered herbaceous plants, although present at all sites, generally comprise less than 5% ground coverage.

2.2. Experimental design and treatment establishment

The experiment was a split-plot with a 3 × 3 × 2 factorial treatment design. Treatments included 3 levels of soil compaction (none, moderate, severe), 3 levels of OM retention (high – OM2; moderate – OM1; none – OM0), and 2 plant diversity treatments (planted trees only, trees and competing vegetation). Compaction and OM retention treatments were randomly assigned to nine 0.4 ha whole plots per site, with each plot divided into split-plots randomly assigned to the plant diversity treatments (18 split plots per site; Fig. 2b). Each split plot contained a 0.05 ha inner plot for non-destructive measurements (e.g., tree growth, O horizon depth) surrounded by an outer plot (0.15 ha) for destructive sampling (understory vegetation biomass harvest). Buffer strips surrounding each whole plot were 7-m wide or greater. Each site was a random block.

Ground equipment was restricted from entering plots during harvesting operations. Although time consuming and technically challenging, this ensured little if any compaction within plots prior to treatment. Conduit pipe (1.2-cm-diam. × 1.5 m) was placed vertically in each plot corner as a visual marker to help harvest operators avoid entering within plot perimeters. Buffer areas between plots were harvested first by directional falling, ensuring that no tree landed within a study plot. Whole trees were then removed to designated landings. Once the buffer areas were harvested, all trees within plots were hand felled, with smaller diameter trees directionally cut before falling larger-diameter trees perpendicular to the small-tree layer. This pattern prevented the larger trees from striking the ground and causing unwanted compaction. All trees were then lifted off the ground (no skidding or excessive soil disturbance allowed within plots) using either ground-based, cable, or helicopter logging depending on local site preferences and available equipment. Ground-based logging used a heel boom loader (excavator) with a 10- to 15-m reach to lift logs from plot interiors

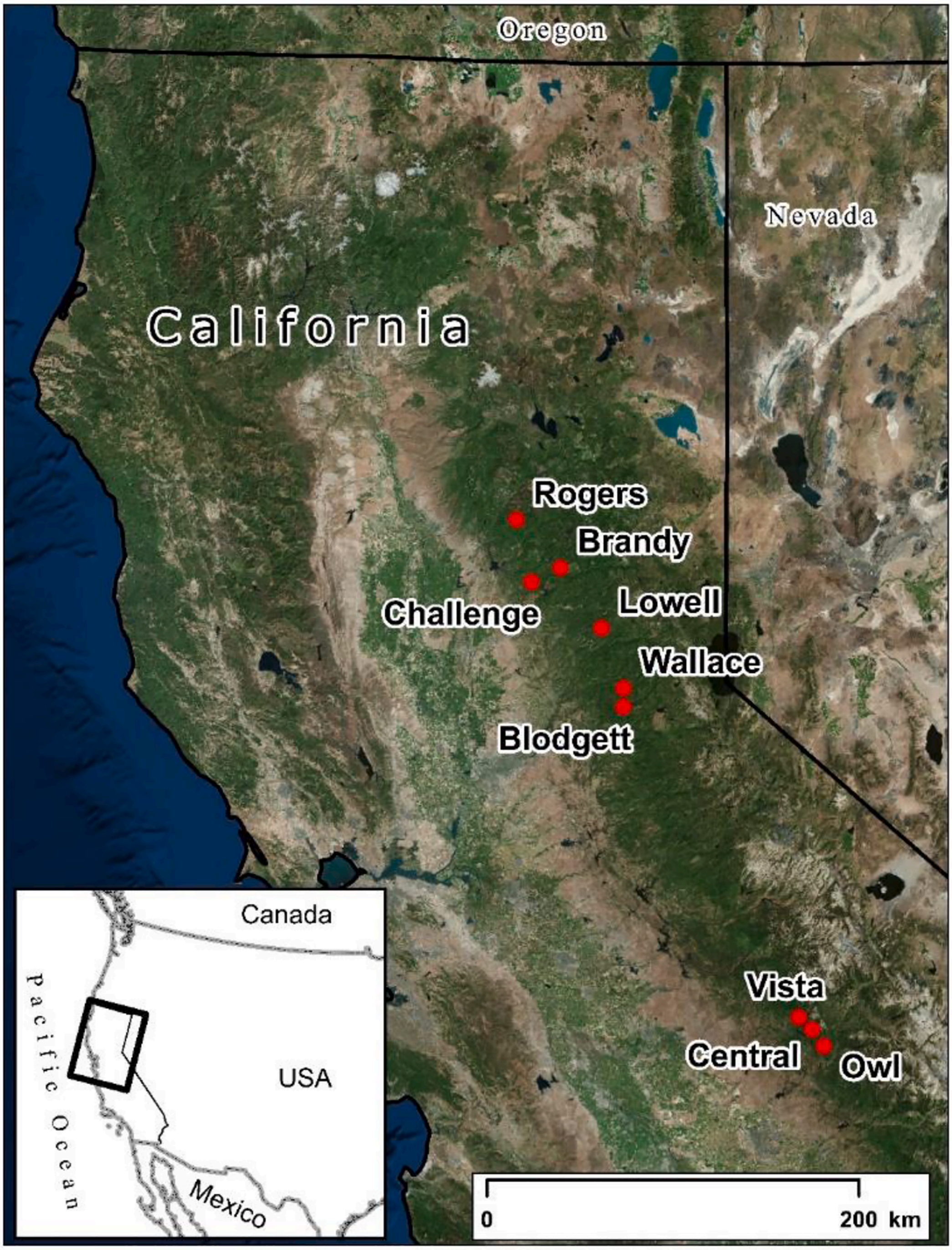

Fig. 1. Study sites along the western slope of the Sierra Nevada.

completely off the ground. A rubber-tire skidder was used to remove logs near plot exteriors, again ensuring that logs did not disturb the ground within a plot. This harvest method was used on all plots, regardless of treatment.

2.2.1. OM retention treatment

Three retention treatments were achieved during harvesting. (1) OM2: all tops (<7.5 cm diam.) and limbs were lopped with a chainsaw and left in place. Slash material that landed outside of the plot boundaries was returned by hand, but only if the originating tree was cut from within a plot boundary. (2) OM1: entire trees (including tops and branches) were removed from plots to nearby landings. (3) OM0: in addition to whole-tree removal, all O horizon material (litter and duff) was removed by hand, leaving exposed mineral soil. Surface organics from small areas (about 3 m × 3 m) were raked onto tarps, hand carried from plots, and piled in windrows in adjacent buffer zones. This process was repeated until the mineral soil was exposed across an entire plot.

2.2.2. Compaction

Compaction treatments were installed following harvesting and OM removal (Fig. 2a). Treatments included: (1) 'No Compaction'; (2) 'Moderate Compaction' – 7 passes by a 9.5 Mg vibrating drum roller (15.9 Mg drum roller at Challenge only) mounted to the front of rubber-tire tractor, applied uniformly across entire plots (see Fig. 2a); (3) 'Severe Compaction' – 21 passes of a 15.9 Mg vibrating drum roller across entire plots. These specifications were determined necessary to meet

Fig. 2. Severe compaction prior to planting (upper left image); maximum OM retention (middle left image); bare soil (OM0) and low plant diversity in foreground, high plant diversity in background (bottom left image); 15-ha LTSP installation at Lowell on the Tahoe National Forest, one of nine study sites (right image).

Table 1
Site and soil (0–30 cm depth) characteristics and study establishment year at the California Long-Term Soil Productivity installations. Soil texture abbreviations: L (loam); CL (clay loam); SL (sandy loam); SiCL (silty clay loam).

Site	Elev. (m)	Annual precip. (cm)	Site index (m at age 50)	Soil series	Soil texture	Clay (%)	OM (%)	Rock (%)	pH	O horizon mass ($Mgha^{-1}$)	Est. year
Blodgett	1320	165	30	Cohasset	L	15	12	5	5.8	79	1994
Brandy	1130	190	29	Cohasset	CL	36	9	3	5.7	66	1995
Central	1685	114	24	Dome, Chaix	SL	5	7	7	6.1	80	1993
Challenge	790	173	28	Cohasset	SiCL	34	8	26	5.8	61	1991
Lowell	1270	173	25	Cohasset	L	20	8	2	6.0	84	1995
Owl	1805	114	23	Dome, Chaix	SL	8	6	20	6.0	72	1993
Rogers	1200	170	27	Chaix	SL	7	5	2	6.0	77	1996
Vista	1560	76	18	Dome	SL	6	6	11	6.2	73	1993
Wallace	1575	178	21	McCarthy	SL	10	12	15	6.2	115	1993

80% root-limiting bulk density (see Daddow and Warrington, 1983) for Severe Compaction and the mid-point bulk density between Severe Compaction and No Compaction for the moderate treatment. Two additional prescriptions were identified in preliminary testing as mandatory to meet our compaction goals: (1) forest floor material completely removed from all plots prior to compacting, (2) soil moisture content near (but not above) field capacity at the time of compacting. Compaction began immediately after soil water drainage in the spring (or after saturating fall rains at the 3 southern Sierra sites), and was typically completed within 7 days, avoiding excessive soil drying. The requirement of removing the forest floor prior to compacting was a consequence of the thick O horizons in these mature forests that protected the mineral soil from compaction forces regardless of heavy equipment type or number of passes. Surface organics were re-applied to OM2 and OM1 plots once compaction was completed; forest floor was applied first, followed by the woody slash for the OM2 treatment only. No organic material was replaced on OM0 plots.

2.2.3. Plant diversity treatment

Plant diversity variation was achieved after other treatments were applied and plots were planted. (1) “Planted trees and competing vegetation” (hereafter, “Trees and shrubs”) – competing vegetation was allowed to develop naturally for the length of the study (see Fig. 2c). (2) “Planted trees only” – all competing vegetation was eliminated by hand grubbing or herbicide application for 5 years following tree planting. Herbicide applications included directed spraying of Garlon 4 plus Roundup (tank mixture of label-recommended concentrations) with cut-and-daub applications of Garlon 3 at sites with competing hardwood vegetation. Hand tools (McCloud, Polaski, weed whacker) were used to grub competing vegetation within a 1.5-m radius around each tree seedling at sites where herbicide use was not an option (Central, Owl, Vista). After the initial treatment, vegetation control was repeated for five years on an as-need basis following semi-annual visual inspections of plant recovery.

Two-year-old seedlings were planted at a 2.4 × 2.4 m spacing, with an equal distribution of ponderosa pine, white fir, Douglas fir, sugar pine, and giant Sequoia (*Sequoiadendron giganteum*) at all sites, except for giant Sequoia at Challenge and Rogers, and Douglas fir at Central, Owl, Vista, and Wallace. A power-auger (15-cm diam.) was used to dig planting sites on all plots since hand digging was essentially impossible in compacted soil. To ensure full stocking, an extra ponderosa pine seedling was planted 0.3 m away from every planting spot. These seedlings were retained only if the target seedling died, otherwise they were eliminated by the third growing season.

2.3. Soil sampling and analyses

Twenty-seven replicate samples were collected from each split-plot using a 7.5-cm diameter bulk density corer. This included 9 samples each from 0 to 10, 10–20, and 20–30-cm depths in the mineral soil. Repeated sampling dates were year 0 (pre-treatment), year 10, and year 20. Replicate samples within each soil depth were composited, resulting in a total of 1458 composite samples for analyses (3 depths × 18 treatments × 9 sites × 3 sampling dates). All samples were air dried at 20 °C before transporting to our laboratory in Redding, CA for processing.

Soil samples were oven dried at 105 °C for 24 h and weighed. Bulk density of each composite sample was calculated as oven-dry weight divided by its combined volume. Samples were then sieved (2 mm), and the fine (<2mm) and large fractions weighed separately. Fine fraction bulk density was calculated as fine fraction dry weight/ (total soil volume – large fraction volume). Large fraction volume was determined by water displacement and was also used in calculating particle density (large fraction weight/volume). Soil porosity was determined as 1 – (total bulk density/particle density), where particle density was the mean value for each site.

Organic C and N concentrations were determined on fine fraction samples by dry combustion using a CNS analyzer. Concentrations were converted to total content by multiplying by the fine fraction bulk density of each sample.

Relative bulk density (RBD), an index of compaction severity, was calculated as the field-derived bulk density divided by the maximum bulk density possible for a given soil type (e.g., a RBD of 1.0 occurs when a field soil has been compacted to its maximum density) at the study mid-point, year 10. Maximum bulk density was determined for each soil type using the Proctor test (ASTM D698). Briefly, moist soil was placed in a metal cylinder (929 cm^3) and compacted by dropping a 2.5 kg weight 25 times from a height of 30 cm above the soil surface. Soil dry weight and volume were determined and maximum bulk density was calculated. The procedure was repeated with increasing soil water content until a maximum bulk density was obtained.

O horizon depth (combined litter + duff) was measured at 30 systematically located points per split plot at year 20. Two sites were omitted (Blodgett, Brandy City) due to wildfire evacuations at the time of sampling. Average depth per split plot was converted to mass by multiplying by plot-specific bulk density values, determined by collecting, drying (65 °C for a minimum of 72 h), and weighing all O horizon organics within 30 × 30 cm frames (8 samples per split plot).

2.4. Data analysis

Treatment effects on soil C, N, bulk density, and porosity were analyzed as repeated measures using mixed model analysis of variance (PROC MIXED in SAS Institute version 9.4). Treatment combinations and year of sampling were considered fixed effects; sites and plots within sites were random effects. Data from each soil depth were analyzed separately. We considered pre-treatment data as a sampling date (Year 0) in ANOVA, not as a covariate. Thus, treatment main effects were disregarded in these analyses because they included both pre-treatment and post-treatment data. Instead, temporal changes in soil properties (i.e., resilience by year 10 or 20) were determined using multiple comparisons with Tukey's adjustment when F tests indicated significant treatment × time interactions at $\alpha = 0.05$. All data were evaluated for normality by visual inspection of normal quartile plots and residual histograms, which led to log transformations of soil C and N data. Pearson's correlation coefficient tests were used to determine whether treatment effects on soil C, N, or bulk density were related to soil clay or OM content across the nine LTSP sites.

3. Results

Significant treatment × time interactions for soil C, N, and bulk density were found in repeated measures analysis (Table 2), indicating that main treatment effects (compaction, OM retention, or plant diversity) resulted in year 10 or 20 that did not exist prior to treatment. All 3-way and 4-way interactions were non-significant and, as a consequence, the effects of compaction, OM retention, and plant diversity are reported separately in the following sections.

3.1. Compaction

Soil bulk density was 18% greater for severely compacted compared to non-compacted plots in the surface 30 cm depth by year 10 (ranging from 10 to 29% greater across sites; Fig. 3a and 4). This response was consistent for each soil depth. Some recovery was found by year 20 (Fig. 4), as compacted plots had 13% higher bulk density compared to non-compacted plots (ranging from 2 to 17%). Interestingly, moderate and severe compaction treatments had comparable bulk densities throughout the study despite their differences in treatment intensity (7 equipment passes for moderate compaction versus 21 passes for severe compaction). Compaction-caused increases in bulk density were not significantly correlated with site clay ($r = 0.66$, $p = 0.053$, $n = 9$), OM ($r = 0.31$, $p = 0.423$, $n = 9$), or rock content ($r = 0.27$, $p = 0.477$, $n = 9$).

Relative bulk density was 17–20% greater for moderate and severely compacted plots compared to non-compacted plots (Table 3). Variation in RBD was considerable among the nine sites, with severely compacted plots ranging from 0.69 (Brandy) to 0.94 (Challenge).

Total porosity in the surface 30 cm averaged 61 ± 2% prior to treatment, with a range from 56 to 71% across sites. By year 10, porosity declined to 56 ± 2% for moderate compaction and 54 ± 2% for severe compaction. Both compaction treatments had 56 ± 2% porosity at year 20, whereas non-compacted plots remained unchanged throughout the study (61% porosity).

Soil C and N concentrations were similar among compaction treatments regardless of soil depth or year (p greater than 0.19; Table S2). However, converting C concentrations to total content resulted in 15–17% greater C for severely compacted plots than non-compacted plots in the surface 0–10 cm depth ($p < 0.05$; Fig. 3b), attributable to treatment differences in bulk density (Fig. 3a). Similar differences in total soil N content were found among compaction treatments in the surface 0–10 cm depth, although they were not statistically significant (Fig. 3c).

3.2. OM retention

An incremental mass increase of 80 Mg ha^{-1} was found among treatment at the beginning of the study (OM0 < OM1 < OM2; Fig. 5). Differences in N content between OM2 and OM1 were less exaggerated, reflecting the lower N content of woody slash compared to O horizon residues (145 and 562 ± 37 kg ha^{-1}, respectively). By year 20, O horizon mass remained lower for OM0 (21 ± 1 Mg ha^{-1}) compared to OM1 (28 ± 2 Mg ha^{-1}) or OM2 (37 ± 2 Mg ha^{-1}).

Table 2
Probability values and numerator degrees of freedom for treatment interactions for soil C, N, and bulk density at three soil depths (0–10, 10–20, 20–30 cm).

		Carbon			Nitrogen			Bulk density		
Source	df	0–10	10–20	20–30	0–10	10–20	20–30	0–10	10–20	20–30
Year × OM	4	**0.001**	**0.001**	**0.001**	**0.012**	**0.002**	**0.002**	**0.001**	**0.001**	**0.001**
Year × Compaction (C)	4	**0.001**	**0.002**	0.306	0.107	0.099	0.669	**0.001**	**0.001**	**0.001**
Year × Vegetation control (VC)	2	0.129	**0.012**	0.265	0.458	0.386	0.632	**0.004**	0.078	**0.050**
Year × OM × C	8	0.786	0.457	0.535	0.899	0.439	0.272	0.617	0.164	0.086
Year × OM × VC	4	0.689	0.824	0.714	0.969	0.492	0.373	0.979	0.544	0.543
Year × C × VC	4	0.911	0.525	0.402	0.861	0.291	0.226	0.702	0.611	0.934
Year × OM × C × VC	8	0.498	0.167	0.880	0.972	0.380	0.813	0.330	0.958	0.981

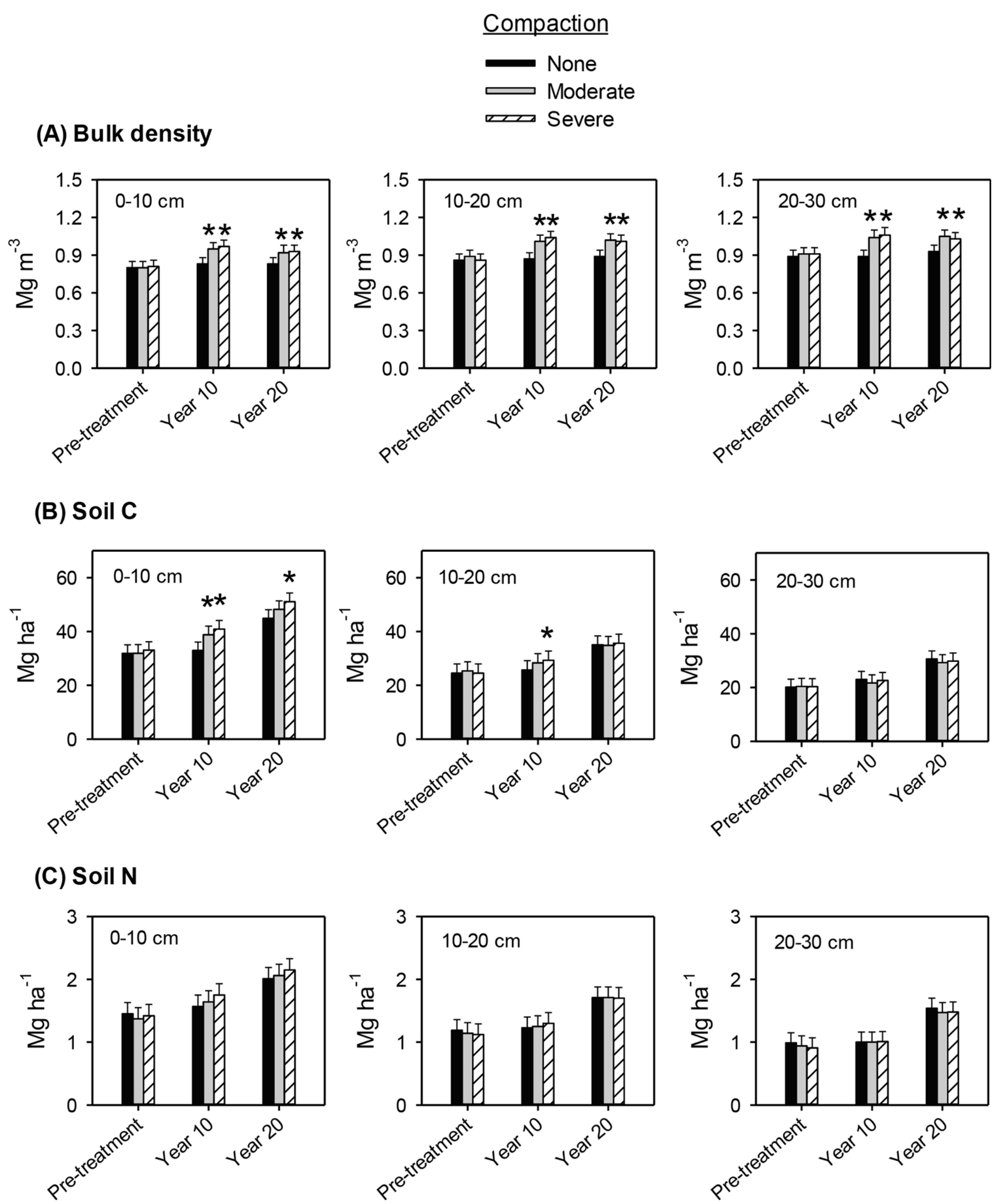

Fig. 3. Main effect of compaction on soil bulk density, C, and N by soil depth and date of sampling across all OM and vegetation control treatments. Bars are least square means with s.e. (n = 9); asterisk (*) represents significantly different from the non-compacted control ($p < 0.05$) within a soil depth and sample date.

Bare soil (OM0) resulted in a 13% increase in soil bulk density in the surface 0–10 cm depth compared to OM2 or OM1 treatments at year 10 and 20 (Fig. 6a). No differences among treatments were found below this soil depth by year 20.

Soil C content (Fig. 6b) and C concentration (Table S3) were significantly reduced by the OM0 treatment. Interestingly, the primary effect

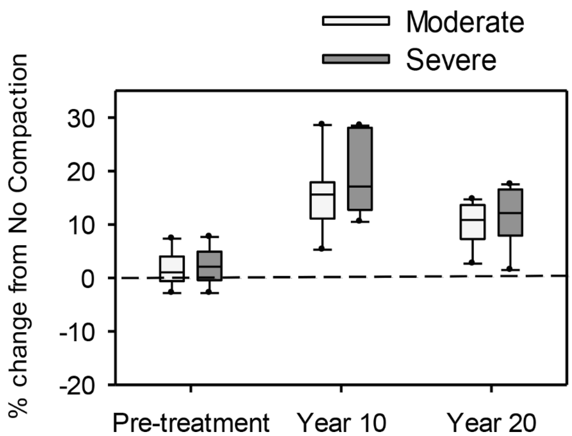

Fig. 4. Percent change in soil bulk density (0–30 cm depth) for moderate and severe compaction treatments relative to non-compacted control across all OM and vegetation control treatments. Box plots represent the variation in bulk density among LTSP sites (n = 9), before and after treatment. Data for each of the 9 sites are presented in Table S1.

Table 3
Compaction severity at the LTSP sites. Relative bulk density is the ratio of the field-measured bulk density (0–30 cm soil depth at year 10) to the maximum bulk density determined by the Proctor method. Values are in bold if they are equal to or greater than 0.80 (80% of the maximum bulk density).

Site	Relative bulk density No compaction	Moderate compaction	Severe compaction
Blodgett	0.68	**0.80**	0.76
Brandy	0.53	0.69	0.69
Central	0.75	0.79	**0.86**
Challenge	0.73	**0.83**	**0.94**
Lowell	0.65	0.74	0.75
Owl	0.66	0.73	0.73
Rogers	0.75	**0.88**	**0.89**
Wallace	0.57	0.68	0.73
Vista	0.69	**0.85**	0.79
Average (s.e.)	0.66 (0.03)	0.77 (0.02)	0.79 (0.03)

was not observed until 20 years after treatment, at a time when the litter layer was re-accumulating. By year 20, OM0 had 15% less total C compared to either OM2 or OM1, ranging from 8 to 26% lower across the 9 sites (Fig. 7, Table S4). No differences in soil C were found between OM2 and OM1 for the length of the study. The OM0 treatment also had 10% less total N content compared to OM2 or OM1 (Fig. 7), although the difference was only significant at a soil depth of 10–20 cm (Fig. 6c). In comparison, N concentrations were significantly lower for OM0 than either OM2 or OM1 at all soil depths by year 20 (Table S3).

3.3. Plant diversity

No significant differences in bulk density were detected between diversity treatments either before establishment or at year 10. By year 20, bulk density was 7% greater for low (trees only) compared to high plant diversity (0.98 and 0.92 Mg m^{-3}, respectively). Although not a large effect, the difference was significant at 0–10 and 20–30 cm depths (Table 2). This was presumably explained by lower soil C input in the absence of shrub litter and roots, although the difference in soil C between low and high diversity treatments at year 20 (3.9 and 3.6 Mg m^{-3}, respectively) was not statistically significant except at the 10–20 cm depth (Table 2). All other soil measures were nearly identical between plant diversity treatments (±5% or less) within each soil depth and sampling year.

4. Discussion

Results from our study provide an interesting perspective to view the original LTSP hypotheses. Thirty-two years ago, Robert Powers and colleagues established a network of 100 + affiliate sites in U.S. and Canadian forests to identify the limits of forest soil disturbance. Their first hypothesis was that extreme changes in soil porosity and OM content have lasting effects on site productivity by altering soil, air, nutrient balance, and energy flow, with severe compaction and removal of surface OM down to bare soil providing the extreme treatments. After 20 years at the California installations, it is evident that even the extreme treatments may not have fully pushed the soils to their threshold limit, and although changes in soil physical properties were substantial, they were arguably moderate in effect (as discussed below), ultimately having no detrimental impact on vegetation growth (Zhang et al., 2017). The second hypothesis was that any negative impacts from harvesting are reversible with time, which speaks to soil resilience and to the importance of maintaining long-term research sites (Knoepp et al. 2019). Here, our results partially support their hypothesis – bulk density recovered some between year 10 and 20, although full recovery, if it happens, will require more time. By comparison, soil C and N content were mostly unaffected by the LTSP treatments, disallowing any test of resilience. An interesting exception was the 10–25% decline in soil C by year 20 following removal of the O horizon (OM0), where little recovery has been noted to date (Table S4). Finally, their third hypothesis stated that impacts to soil properties are not universal, instead they vary by climate and soil type. Our results did not confirm this within the Sierras. Instead, treatment responses were generally consistent among sites despite a moderate range in annual precipitation and a considerable range in soil clay and OM content. Two possibilities come to mind as potential explanations: first, the dominance of a Mediterranean climate at all locations (dry, hot growing seasons) likely overwhelmed the site differences in total precipitation and soil properties, and second, the core measurements we tested (BD, total porosity, soil C and N content)

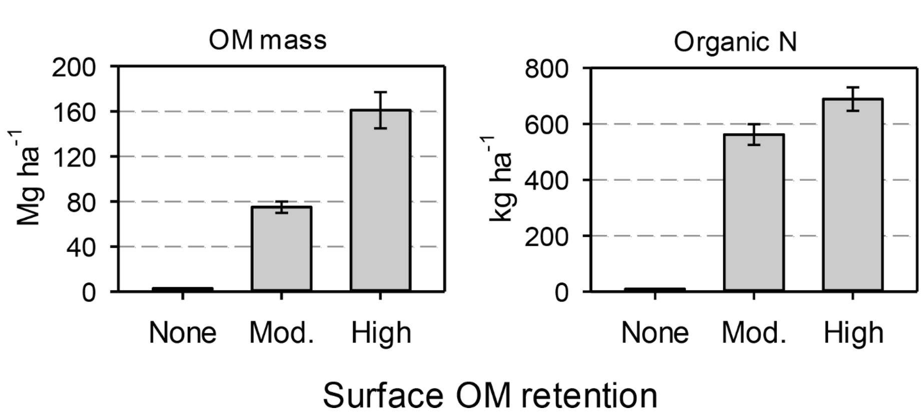

Fig. 5. Surface OM mass and N content at the onset of the study (n = 9). Data from Powers (2006).

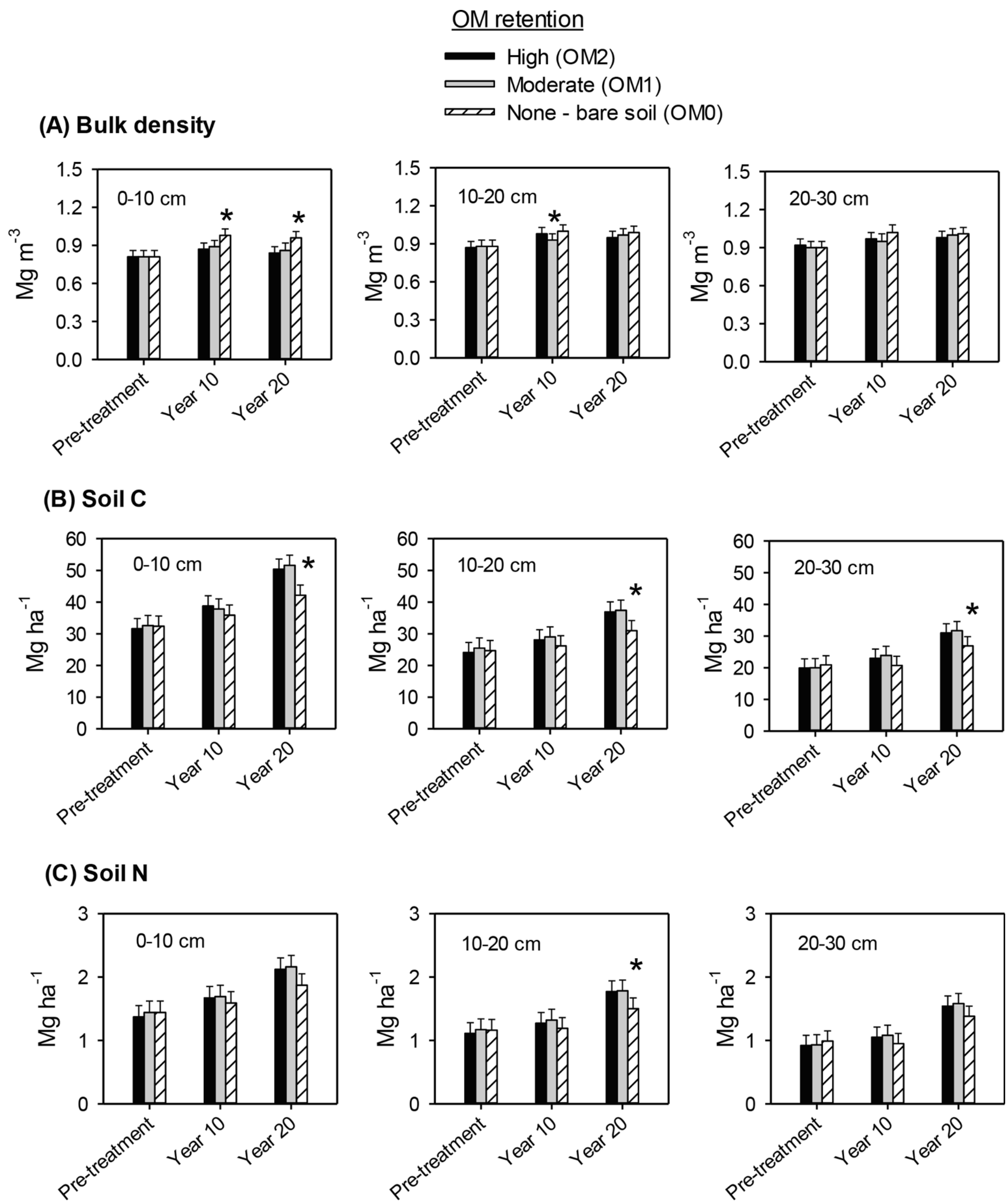

Fig. 6. Main effect of OM retention on soil bulk density, C, and N by soil depth and date of sampling across all compaction and vegetation control treatments. Bars are least square means with s.e. ($n = 9$); asterisk (*) represents significantly different from OM2 – high retention treatment ($p < 0.05$) within a soil depth and sample date.

were too insensitive to detect treatments effects, whereas other soil measures (e.g., nutrient turnover, OM decomposition rate, macroporosity, microbial activity and composition) might have told a different story (e.g., Hartmann et al. 2012). Alternatively, the high level of variability in soil properties at our study sites may have limited the ability to detect modest treatment effects.

4.1. Compaction

Soil at our study sites was severely compacted by heavy equipment (Fig. 2). As anecdotal evidence, early-on attempts to collect soil samples using slide-hammer corers were met with unyielding resistance, while preparing planting spots required the use of a power auger because traditional hand-planting tools were ineffective. These difficulties corresponded with bulk density values as much as 29% greater compared to non-compacted soil at year 10 and soil strength estimates well above 3 MPa at several of our sites (Busse et al., 2017), or about 3-fold higher than non-compacted plots. Average bulk density increase across sites was 18% for severe compaction and 16% for moderate compaction at year 10. These increases were consistent to a depth of 30 cm and fell within the range of post-compaction bulk densities found for the entire LTSP network (Page-Dumroese et al., 2006).

As impressive as the changes in bulk density were, corresponding changes in total soil porosity (11% decline), C content (7% increase), and soil N content (1% increase) were less exaggerated. Further, despite its moderate decline, porosity remained above 50% of the total volume in compacted soil. How this translates to gas, water, and root movement is difficult to predict given that total soil porosity values fail to identify important shifts in pore-size distribution (i.e., reduced macroporosity; Kim et al. 2010). To this point, Paz (2001) found a net reduction of only

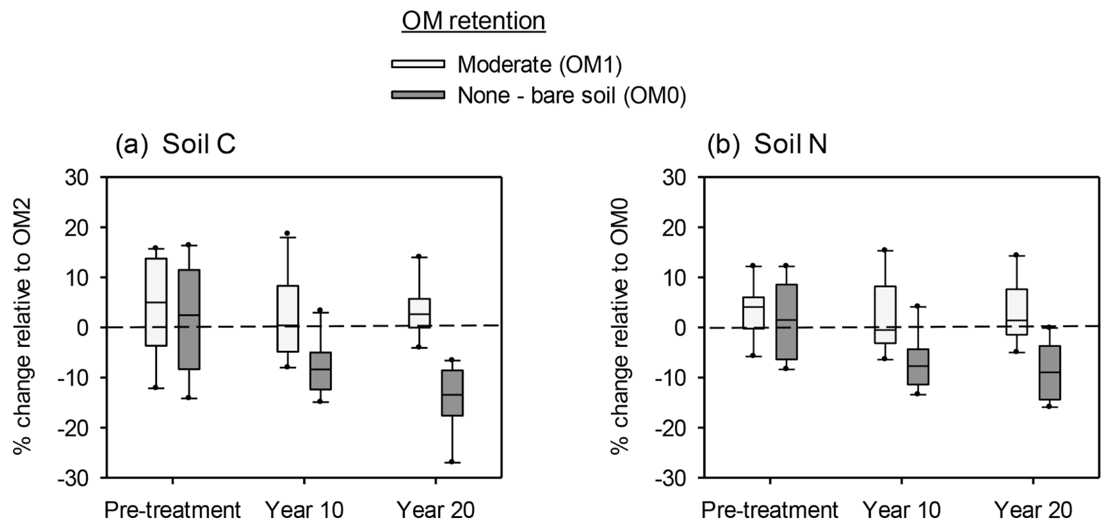

Fig. 7. Percent change in soil C and N (0–30 cm depth) for moderate OM retention (OM1) and bare soil (OM0) relative to the high OM retention treatment across all compaction and vegetation control treatments. Box plots represent the variation in C or N content among LTSP sites (n = 9), before and after treatment. Data for each of the 9 sites are presented in Table S4.

8% total porosity was associated with a 43% decline in macroporosity and compensatory increases in meso- and micro-pores at 3 California LTSP sites (Brandy, Blodgett, Lowell). Clearly, additional research is needed on pore-size distribution change in managed forests to understand how, when, and where this complex rearrangement of soil structure will modify fine-scale water, gas, nutrient, and energy flow, and, ultimately, forest health and production.

Relative bulk density (field-measured BD divided by maximum BD) is an ancillary measure of soil compaction, essentially a coarse-scale index of disturbance severity that allows for comparisons across soil types and textures (Bulmer and Simpson, 2010). Average RBD across our sites was 0.79 (range: 0.69–0.94) for severely compacted plots, which approximates the growth-limiting threshold of 0.80 suggested for forest soils (Zhao et al., 2010). Recent evidence from LTSP sites in British Columbia, however, indicated that vegetation growth declines occur at RBD values above 0.86 (Kabzems, 2012; Kranabetter et al., 2017). Thus, our original target of 80% root-limiting bulk density for severe compaction (comparable to 0.8 RBD) may have underestimated the plant-growth threshold, helping to explain why 20-year vegetation biomass (Zhang et al. 2017) and conifer rooting distribution (Busse et al., 2017) at the California sites were not reduced by compaction. Interestingly, Scott (2016) found that shrub biomass, but not tree biomass, was reduced in LTSP-compacted soil. Differential responses among plant lifeforms and species is not uncommon in disturbed soil (Tracy et al., 2011; Kranabetter et al., 2017), although the mechanisms responsible for these differences – whether a function of unique mycorrhizal associations, rooting architecture, root turgor, and/or nutrient and water demands – are unclear and would benefit from further study.

A few “lessons learned” during treatment installation are worth noting. First, we were unable to meet compaction targets at any site without first removing the O horizon down to bare soil. Thick litter and duff layers (6–12 cm) after 100 + years of forest development cushioned heavy equipment traffic enough to limit the treatment effectiveness well below our BD targets. This observation underscores the importance of retaining surface organics during harvesting in order to avoid unwanted compaction (Han et al., 2009; Page-Dumroese et al., 2010) and also highlights the difficulty in compacting soils with high organic matter and root content (Krzic et al. 2004). Second, compaction targets were unattainable unless soils were near field capacity moisture content when treated. This comes as little surprise; it is well-established that water acts to reduce friction between soil particles, allowing for easier soil compaction compared to drier soil (Graecen and Sands, 1980) and, hence, the long-standing best practice of harvesting when soils are dry (or frozen) in order to limit compaction (Cambi et al., 2015). Thus, these best practices – harvesting on top of a reasonably intact O horizon when soils are dry or frozen – are encouraged in order to avoid unwanted compaction in Sierran soils.

Little change in total soil C and N was found in the surface 30 cm after 20 years of compaction, which extends the 5-year LTSP results showing no response by C or N to compaction at sites across the US and Canada (Sanchez et al., 2006). Scott et al. (2014) also found little compaction-related change in total C after 15 years at sites across southeast US. Collectively, these findings support the general conclusion that harvest disturbance often has little or variable impact on total soil C content (Nave et al. 2010). Changes in finer-scale C processes such as root turnover, heterotrophic respiration, gas exchange, and altered physical protection of C in micro-aggregates are known to occur in compacted soil (Alemeda et al., 2012; Hartmann et al., 2014; Epron et al., 2016), yet their combined influence on total C sequestration is difficult to predict (Beylich et al., 2010) and, in the case of the California LTSP sites, was not evident. It is important to acknowledge that the LTSP study examines the singular effects of compaction, separate from other known physical effects such as soil mixing, churning, or displacement. Harvested trees were lifted off the soil surface prior to compacting, thus isolating compaction from these often co-occurring processes. For this reason, any comparison of our results with those from operational studies of skid trails, where multiple disturbance processes typically occur, requires caution.

4.2. *OM retention*

Harvest slash may benefit soil as a source of C and nutrients, a mulch layer to help limit water loss and temperature extremes, and a physical layer to protect soils from machinery traffic and erosion loss (Cambi et al., 2015). It is unclear whether these advantages universally translate to measurable changes in soil properties or stand growth (Vance et al., 2018), leading to a general agreement that slash-retention effects are best considered on a site-by-site basis (Mayer et al., 2020). At the California LTSP sites, we found soil C, N, and BD nearly identical between slash retention treatments (OM2 vs OM1) through 20 years, supporting other LTSP examples of limited effects of slash retention (Scott et al., 2014; Slesak et al., 2016; Morris et al., 2019), and suggesting that slash is inconsequential to the fertility of these soils. If anything, its contribution as a fuel hazard represents a point of concern in the management of these fire-prone forests. We believe the limited response to slash addition was a result of the relative fertility of the Sierran LTSP sites compared to nutrient-poor sites, which often benefit from slash retention (Achat et al. 2015). As an example, harvest slash N at our sites was less than 0.2 Mg ha^{-1}N compared with 0.6 Mg ha^{-1}N in the O horizon and 3 Mg ha^{-1}N in the mineral soil (0–30 cm depth), or about 5% of the total N pool (and even lower if the entire soil profile had been accounted for).

Complete removal of harvest slash and the O horizon (OM0), on the other hand, resulted in a shift in soil properties by year 20. Bulk density increased while mineral soil C content was 15% lower compared to either OM2 or OM1, a trend that was consistent across sites and soil depth. Early findings by Paz (2001) also showed higher soil temperatures and lower available soil water during the growing season in the absence of an O horizon at a subset of these sites. We assume that the delayed timing of the soil C response – not statistically significant until year 20 – reflects the slow turnover of forest floor organics in the Mediterranean climatic region of California prior to its eventual incorporation in surface mineral soil. Whether this treatment effect will continue is unclear, particularly now that an O horizon is developing on OM0 plots. Still, the O horizon is an integral component of forest soil (Binkley and Fisher, 2019), serving numerous ecological benefits such as soil temperature and moisture moderation, erosion protection, and nutrient source, and our results support this well-established concept. Curiously, the presence of an O horizon did not significantly improve 20-year aboveground biomass at our sites (Zhang et al., 2017) despite its benefit to soil C and N content, an acknowledgement that the O horizon is only one of many site factors affecting vegetation growth. Nevertheless, Zhang et al. (2017) did point out a modest trend of reduced biomass in the absence of an O horizon, suggesting a possible N deficiency may eventually affect stand development.

5. Conclusion

Findings from the LTSP installations in the California Sierra Nevada showed moderate, at most, effects of compaction, OM retention, and plant diversity on core soil physical and chemical properties. Results after 20 years include (1) compaction led to a prolonged increase in soil bulk density of 10–20% relative to non-compacted soil, with a moderate decline in porosity and little effect on soil C or N concentration and storage. Bulk density recovery remained incomplete by year 20. (2) Slash retention and plant diversity treatments did not alter soil properties at year 10 or 20. (3) Complete O horizon removal (bare mineral soil) led to a decline in soil C storage and to a lesser extent N storage in the upper 30 cm soil profile that progressed with time. These results were consistent across Sierran sites ranging widely in clay and OM content, presumably a reflection of the dominant role of a seasonally dry Mediterranean climate plus the tolerance of these mostly fertile soils to compaction and OM removal. That few differences in vegetation growth were found among treatments in an earlier study by Zhang et al. (2017) further confirms the tolerance of these forests to harvest-related disturbance.

Taken at face value, the results showed that compaction and slash removal are benign disturbances in these systems. We emphasize, however, that the LTSP study is designed to examine a pulse effect – compaction and OM removal during a single harvest – and does not consider added effects likely to occur in Sierran forests such as fire, insect outbreaks, additional harvesting, climate change, or population growth and expansion. Given the likelihood for additional disturbances, we encourage site-specific awareness and documentation of cumulative soil compaction and O horizon loss, whenever possible, for sustaining long-term soil health.

CRediT authorship contribution statement

Matt Busse: Conceptualization, Validation, Formal analysis, Investigation, Writing - original draft. **Jianwei Zhang:** Conceptualization, Validation, Writing - review & editing. **Gary Fiddler:** Conceptualization, Validation, Writing - review & editing. **Dave Young:** Conceptualization, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118851.

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